Chapter

Innovative Double Cathode Configuration for Hybrid ECM + EDM Blue Arc Drilling

Jesus M. Orona-Hinojos

Abstract

Electrical discharge machining is a machining method generally used for machining hard metals, those that would be high cost or have poor performance to machine with other techniques using, e.g., lathes, drills, or conventional machining. Therefore, also known as thermal processes like EDM, Plasma or Laser cutting can be used in drilling operations with poor metallurgical quality on cutting edge and will be necessary complement with other processes such as electrochemical machining (ECM). Both ECM and EDM processes use electrical current under direct-current (DC) voltage to electrically power the material removal rate (MRR) from the workpiece. However in ECM, an electrically conductive liquid or electrolyte is circulated between the electrode(s) and the workpiece for permitting electrochemical dissolution of the workpiece material. While the EDM process, a nonconductive liquid or dielectric is circulated between the cathode and workpiece to permit electrical discharges in the gap there between for removing the workpiece material. Both are principle too different, EC using an electrical conductive and ED using a dielectric medium. But exist a way that can to do a combination of Pulsed EC + ED Simultaneous and allowing the coexist both process, in a semidielectric medium, where both condition exist in the same time, therefore in this hybrid is possible create a tooling device dual cathode for drilling process with promissory advantages fast hole for this innovative hybrid ECDM Simultaneous, this hybrid it's knew as blue arc drilling technology.

Keywords: Drilling, EDM and ECM process, Double Cathode, Hybrid ECDM

1. Introduction

Is known that ECM and EDM are machining processes that each one has reached a maximum in the material removal rate (MMR), mainly due to conditions of electrochemical and physical equilibrium respectively. These processes defined as electrical discharge machining (EDM) and electrochemical machining (ECM) have high adaptability to make some variants of assisted hybrid systems that allow the acceleration of mass transport to improve considerably the metal removal rate measured in mm^3/min. Then those processes present important advantages when combined with other variants such as the use of abrasive materials (G), ultrasound (US), laser projection (LB), and hydrodynamic magnetic force (HMF) that scientific community has reported in the last decades, then the integration is a possible challenge for engineers and technologists today.

The evidence on the growth of these removal speeds regain the interest of the industrial sector, being the advanced hybrid machining processes (HMP) like to EDCM technology that allows them will be competitive on some parameters versus Laser or Plasma thermal cutting with high material removal rate, but with a severe heat-affected zone (HAZ), between 1000 to 1600 μm. While in non-contact cutting processes EDM and ECM the HAZ is minimized below 40 μm. However, in terms of material removed, the ECM has speeds of the order of 100 to 250 mm^3/min, depending on the work material and current density among other parameters. EDM process, the removal speed is between 300 to 600 mm^3/min, depending on the discharge power and duty cycle [1].

Variants to the recently published non-contact machining processes [2, 3] open up new lines of innovation in the use of hybrid high-speed EDM technology in drilling and grinding for: (i) Multi-manufacturing of complex precision 3D with additive-laser. (ii) Manufacture of alloys high strength with friction-free finishes (Ra < 400 nm). An EDM electro-discharge erosion process, also known as Blasting BEAM (Blasting Erosion Arc Machining) [4] is reported, with MRR of the order of 11,000 mm^3/min in Inconel 1718, obtained experimentally.

General Electric Inc. in 2011 showed evidence of technological development of machining for high-speed blades with hybrid EDM in low thermal impact named Blue Arc Machining a device with registration US2010/0126877 A1. GE's laboratory in China achieves MRR in the order of 3,500 to 5,000 mm^3/min.

On the other hand, leading global companies in thermal cutting processes such as TRUMPF Inc. unveiled in 2011, a hybrid Laser/EDM Drilling Cell, with removal capacities of 30,000 to 35,000 mm^3/min, depending on the type of part to be manufactured "light-alloy", "medium-alloy" or "duty-alloy" component patent registration EP1988/0299143 A1 [5]. In other words, conventional laser and plasma thermal processes are also reaching their removal speed limit and are evolving into special hybrids.

A couple of decades ago, advanced materials and cutting precision were intended for components of the aerospace and aeronautical sector, which for safety were manufactured piece by the piece it's known as "aircraft-components", and the manufacturing precision allowed by electro-machining ECM and electrical discharge EDM, presented a good solution, because an aircraft is currently assembled between 2 to 8 months, depending on the size and the commercial nature, that means, assembly of 300 to 1000 Aircrafts per year. While the global automotive sector manufactures 80 a million vehicles per year, according to 2018 records referred to in OICA International Organization of Motor Vehicle Manufacturers [6]. This is where new high-performance materials challenge manufacturing processes as "cutting, forming-stamping, bonding and machining" play an important role. Consequently, manufacturing engineers are challenged to find viable highly innovative solutions.

The simultaneous hybrid ED + EC technologies not exist yet commercially for industrial use, being in development the machining by electrical discharge assisted with simultaneous electrochemical pulses ED + PEC or named Pulsed ECDM, the first of thermal nature of plasma-ionic type and the second electro ionic of chemical nature; is possible will be offered in this decade by the original equipment manufacturing houses (OEMs), for industrial applications.

A recent study called "Special Machine Tool Market by Research" [7], reveals that approximately 78,000 units were sold of special machine tools for the manufacturing of the cell-laser type, plasma cutting machines, EDM cutting machines, cutting machines ECM, Water-Jet Cutting machines, and CMM (Coordinate Measuring Machines), for a world market size with revenues of 9.6 billion dollars. Of which 22% of these units are made up of laser/plasma cutting, 45% are from the EDM process, 6.5% from units sold in ECM, and just over 15% for "Water-Jet" cutting technologies, and 11.5% remaining in coordinate measurement machines (CMM). Laser/plasma cutting tools and EDM are the processes of greater demand; it is a market that has not yet reached maturity with a growth of 7.8% per annum CAGR (Compound Annual Growth Rate).

To improve the application of the cutting process by electro-discharge EDM, it has been proposed to assist it with PEC pulsed electrochemistry, this class of processes is known as hybrid ECDM (Electrochemical discharge machining) or ECSM (Electro-chemical spark machining) as reported [8]. There are two categories of hybrid machining processes (HMP) as shown in **Figure 1**. Relationships of binary and ternary hybrids are based on their physical nature to carry energy (mechanical, chemical, and thermal). The first category of HMP's is that all its constituent processes are directly involved in the removal of material. The second category of assisted HMP's is made up of processes in which the only one of the constituent processes directly remove the material, while the others are only assisting the removal process, changing the machining conditions in an appropriate direction, improving the machining conditions. Some processes such as plastic flow, mechanical abrasion, heating, melting, evaporation, dissolution, manage to change the physicochemical conditions of the material of the workpiece during a machining process [9].

The application characteristics of hybrid processes are considerably different from the corresponding characteristics of the "constituent" processes when these are applied separately. For example, it is established that the productivity of ECM electrochemical machining, when assisted with EDM electric discharge, is 10 to 50 times higher [10, 11].

2. Hybrid simultaneous ED/PEC drilling using double cathode

The pulsed electrochemical machining (PECM) on a simultaneous pulsed train of discharge plasma EDM, on the surface of a workpiece is named simultaneous ED + PEC drilling. Combination electro discharge and chemical machining in low-resistivity deionized water, has been investigated in the last decade to obtain a high material removal rate (MRR) and transfer energy to the workpiece [12].

		ED	LB	EB	PB	CH	**EC**	A	T	US	F
Thermic	ED	**EDM**					**ECDM**	AEGD		UAEDM	
	LB		LBM			LAE	LECM		LAT		
	EB			EBM							
	PB				PBM				PAT		
	CH		ELB			CHM					CHP
	EC	**ECAM**	LECM				**ECM**			USECM	
Mechanic	A	AEDM				MCP	AECH	G		USG	
	T		LAT						T	UAT	
	US	UAEDM	UALBM				USMEC	GUS	UAT	USM	USP
	F					CHP	LAE			USP	FM

Figure 1.
Advanced Hybrid Machining Processes (HMP) El -Hofy [1].

2.1 Configuration double cathode for hybrid S-ED/PEC drilling

The configuration of a hybrid S-ED/PEC process in a semi-dielectric medium comes from a base EDM system, as a scheme is shown in **Figure 2**. The EDM equipment was complemented with two feed inputs: (i) dielectric deionized water (DW) and (ii) low resistivity deionized water (LR-DW), thus causing simultaneous EDM and ECM operating conditions in different regions of a Dual Cathode system. For EDM it is possible to use a graphite electrode in the form of an external head (first cathode), and for ECM an electrode composed of a set of 12 pins mounted on a bronze ring inside the graphite head, the external electrode presents an arrangement of channels that allows movement of the semi-electrical fluid and ionic transfer, these electrodes are arranged in such a way that they connect with an arrow that allows a rotation between 1200 to 1600 rpm, the head is electrically isolated and both samples have electrical continuity fed by a VDC source external pulsed.

In this configuration, a fluid can be fed in two ways. The EDM case feeds: a central inlet deionized water flow V1, through the system of cathodes arranged in a shape concentric with the head of the system. The head speed parameter Vz in the "z" axis constant at 0.5 ± 0.05 μm/s, up to a penetration height of 3 mm (H). On the other hand, stop the S-ED/PEC process, the equipment is configured using an ii) external input flow to the electrode with deionized water of low resistivity LR-DW and it is switched with the second flow V2 to the interior changing the deionized water DW by low resistivity water 0.5 MΩcm LR-DW. Sodium bromide salt (NaBr) in 1.23 ppm TDS was used to adjust the resistivity to 0.5 to 2.5 ± 0.01 MΩcm. NaBr has the ability to solvate ions and, therefore, show a constant electrical conductivity behavior for high temperatures reported by [13].

2.2 Theoretical model S-ED/PEC

The main characteristic of the proposed S-ED/ PEC (Simultaneous Electro Discharge/Pulsed Electrochemical), allows a significant increase in the efficiency of MRR, and a significant reduction in surface roughness, thus providing a better surface finish. It is well known that the EDM process contributes significantly to MRR, as it produces deep layer of heat affected zone (HAZ). While that the main contribution of ECM process as consequence of combining, is the removal HAZ layers allowed roughness less than 2.5 μm (Ra), as reported Levy GN and Maggi F (1990) [14].

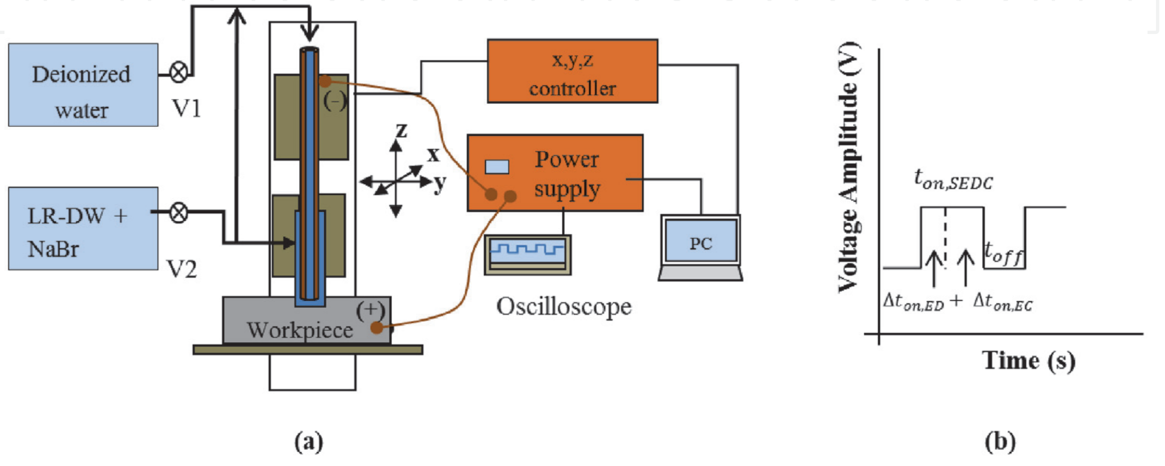

Figure 2.
Experimental scheme of (a) EDM River 300 Cell - Instrumented, (b) ED / PEC open circuit voltage pulsed signal [15].

They conducted a study on W-EDM for the machining of high-quality heat-treated alloy steels. They reported that the HAZ and the solidified layer reach 25 μm. Meanwhile, heat-affected zone with a white layer of approximately 10 μm with high hardness are reported [15]. On the other hand, the novel material removal process of high efficiency by blast erosion arc machining (BEAM), has an extremely higher material removal rate in relation to traditional EDM. However, the thickness of the HAZ caused by BEAM is close to 200 μm. Although it is known that the depth of the HAZ and the re-solidified layer is proportional to the amount of energy used.

Machining by S-ED /PEC, under dielectric conditions of low resistivity results in a phenomenon of physic-chemical activation, on the surface of the material that allows an exchange of advantages of the constituent that substantially improve the removal of material at high speeds with minimal thermal impact. Although, the contributions of the ED and PEC processes are not fully explained in the literature. In this research work, a mathematical model for ED/EC simultaneous drilling is proposed to determine the removal rate and the proportion of energy transferred to the workpiece under a new theoretical model, as well as to minimize the white layer effect to determine the contribution of each process in drilling holes in a High Strength Steels (HSS).

The combination of two phenomena, known as: (i) electro-thermal discharge and, (ii) electro-ionic dissolution, in simultaneous ED/PEC, increases the speed of material removal through chemical and physical activation of the metal surface, due to the exchange of advantages. A conceptual scheme of the removal mechanism for drilling by EDM and comparatively by S-ED/PEC is presented in **Figures 3** and **4**. The initial surface condition for $t_{i=0} = 0$, the volume elimination is VR = 0, as presented in **Figure 3(a)** for ED. After the first discharge condition $t_{i+1} = t_{on,ED}$ the volume $VR_1 = VR_s$ (elimination of volume by sparks), as indicated in **Figure 3(b)**. It is known that for every spark produced for EDM, this generate high roughness. In **Figures 3(c)** and **(d)**, the second discharge condition is $t_{i+2} = 2t_{on,ED}$, and the second volume is defined as: $VR_2 = \varphi VR_s$, where the fraction φ <1, $VR_2 < VR_1$ and the volume release is not equal to the first download.

On the other hand, the simultaneous ED / PEC drilling for the ED condition reveals that the surface initially for $t_{i=0} = 0$, and VR = 0, as shown in **Figure 4(a)**. After the first discharge for the first time stage $\Delta t_{on,ED}$, the volume removal is $VR_{s1} = VR_s$ as **Figure 4(b)**. In the second stage $t_{i+2} = \Delta t_{on,EC}$ there is a change in the elimination of EC by dissolution of the Fe^{+2} ion, then the volume $VR_2 = VR_d$ as **Figure 4(c)** and **(d)**, with a lower surface roughness. Then, the value of the volume fraction is finally φ = 1, and therefore $VR_{s2} = VR_{s1}$, for each S-ED/PEC cycle. Following the EC condition, the surface shows better behavior due to the amount of material removed by the electric discharge process. This lower degree of roughness is produced by ion exchange during the electrochemical dissolution stage of the workpiece.

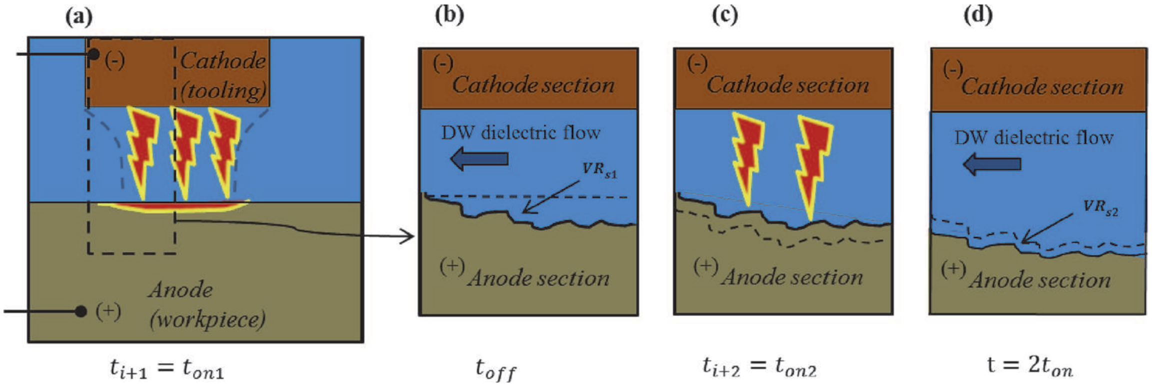

Figure 3.
Diagram for EDM removal mechanism. (a) Initial discharge, (b) EDM first cycle VR_{s1}, (c) EDM second cycle and (d) Surface removal $VR_{s2} = VR_{s1}$ for φ <1 [16].

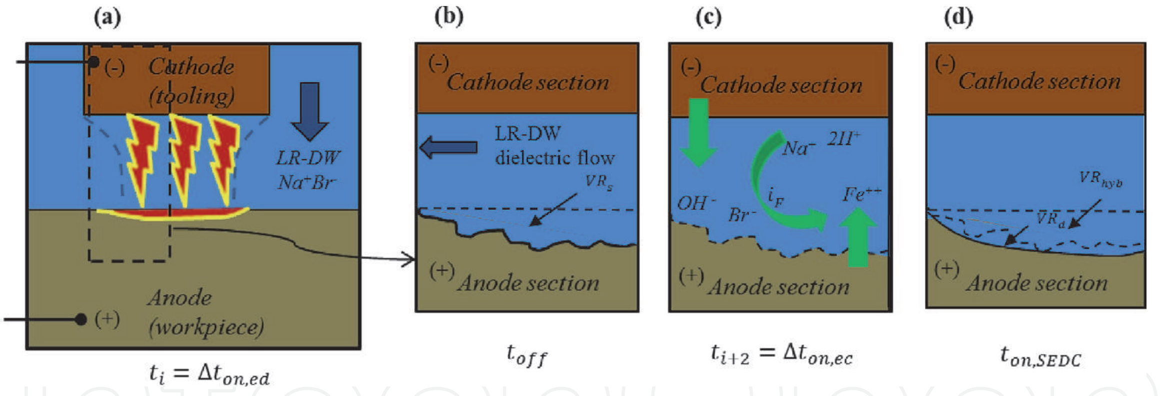

Figure 4.
S-ED/PEC drilling (a) initial discharge ED, (b) removal cycle VR_s for ED, (c) volume VR_d of the removed cycle for EC, and (d) S-ED/PEC total cycle volume $VR_{hyb} = VR_s + VR_d$ for $\varphi = 1$ [16].

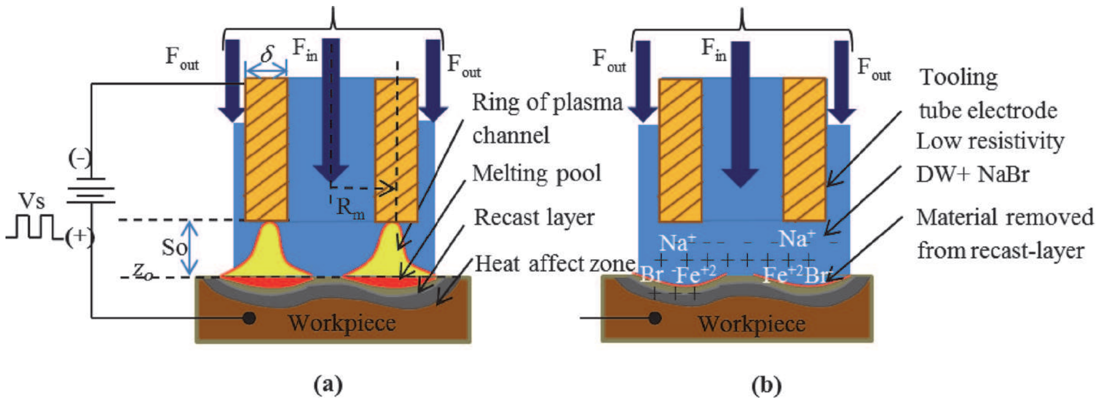

Figure 5.
Tool-workpiece scheme for S-ED/PEC drilling under two divided pulse conditions as (a) Δt_{on1} for ED and (b) Δt_{on2} for EC [16].

2.3 Mathematical model of simultaneous ED/PEC assistance

Figure 5 shows the tool-workpiece scheme for the S-ED/PEC hybrid. There are irregular layers in the order of micro thicknesses located in the active region, due to the electric discharge of the EDM, as seen in **Figure 5(a)**. There are three main layers on the z_o surface after discharge. These include (i) melt layer, (ii) the white layer is a remelting layer, and (iii) the heat affected zone.

Figure 5(b) shows the second mechanism of material removal, which involves the release of atomic layers, which is due to the electro-ionic dissolution process of the ECM. Therefore, the material removal rate per unit area MRR^p $\left[mm^3 \cdot m^{-2} \cdot s^{-1}\right]$ per unit time t [s] is proportional to the cycle energy function $E(t)$ $\left[J \cdot cycle^{-1}\right]$, which is required for machining. As a result, the machinability constant $K_m \left[mm^3 \cdot m^{-2} \cdot J^{-1}\right]$ of this system is obtained the Eq. (1), as was written in the research theoretical model S-ED/PEC [16].

$$MRR^p * t = K_m * E(t) \tag{1}$$

Eq. (2) is used to calculate MRR_{hyb} of low resistivity S-ED/PEC drilling in deionized water (LR-DW), where the pulsed duration takes two relevant conditions, namely (i) $\Delta t_{on,ED}$ for the ED condition and (ii) $\Delta t_{on,EC}$ for the EC condition. Therefore, $t_{on} = \Delta t_{on,ED} + \Delta t_{on,EC}$ is set by the simultaneous condition.

$$MRR_{hyb} t_c = \left(MRR_s^p \Delta t_{on,ED} + MRR_d^p \Delta t_{on,EC}\right) A_T \tag{2}$$

Substituting the respective expressions of Eq. (1), in Eq. (2), the resulting volume of material extracted during S-ED/PEC drilling could be calculated by means of Eq. (3), where MRR_{hyb} is the velocity volume elimination MRR_{hyb}, and K_s, K_d are the machinability constants of the ED and EC subsystems, respectively.

$$MRR_{hyb} = \left[\left(\frac{1}{t_c}K_s * E_s(t)\right) + \left(\frac{1}{t_c}K_d * E_d(t)\right)\right]A_T \tag{3}$$

For which, A_T (mm^2) is the cross-sectional area of the tubular electrode and is represented by Eq. (4).

$$A_T = 2\pi * R_m * \delta \tag{4}$$

Considering R_m (μm) as the average radius of the tool and δ (μm) is the thickness of the tool.

The amount of energy for each subsystem, $E_s(t)$ and $E_d(t)$, for a hybrid S-ED/PEC condition is represented by the terms of Eq. (3), which can be solved using an experimental pulsed electrical signal. It is known that the expression $E_s(t)$ for EDM can be defined by Eq. (5).

$$E_s = \int_0^{ton} I_e * V_s \, dt \tag{5}$$

Where:

$$I_e = f_e * I_p \tag{6}$$

While $E_d(t)$ for ECM it is possible to represent it by Eq. (7) [16].

$$E_d = \int_0^{ton} V_a * i_{o,Fe} * exp\left(\eta_{Fe} * \beta^{-1}{}_{a,Fe}\right)dt \tag{7}$$

Where V_a is the anodic voltage (volts) and I_F is the Faraday current (A) that can be determined using TAFEL Eq. (8).

$$I_F = i_{o,Fe} * e^{\left(\propto\frac{zf}{RT}\right) * \eta_{Fe}} dt \tag{8}$$

$i_{o,Fe}$ is the ion-exchange current (A) and $\eta_{Fe} = \left(\phi_{a,Fe} - \phi^0\right)$ is the overpotential (volts) where $\phi_{a,Fe}$ is the anodic potential and ϕ^0 is the equilibrium potential of the redox reaction with a value of −510 mV for Fe ➔ Fe+2 + 2e.

Was considered the argument $\beta_{a,Fe} = \frac{RT}{\alpha zF}$ where $\beta_{a,Fe}$ ($Volts^{-1}$) represent the TAFEL anodic constant. The value of $\beta_{a,Fe}$ can be estimated assuming the following values. A symmetry coefficient of polarization α is equivalent to ½, ideal gas constant R = 8.314 JK^{-1} mol^{-1}, Faraday's constant F =96487 C mol^{-1}, the electron exchange number z for iron case Fe ➔ Fe+2 + 2e, z = 2, and T is the interphase temperature assumed Temperature of room. Then, this can be estimated as β^{-1} = 31.97 mV as was reported by Winston [17], for a cell S-ED/PEC.

2.4 Simultaneous ED/PEC electro-ionic model

It is possible to determine the fraction contributions of each process for the S-ED/PEC hybrid, where ψ_s (9) is the contribution of the ED fraction and ψ_d (10) is the contribution of the EC fraction. The hybrid process can be expressed as $\psi_s + \psi_d$ = 1. Therefore:

$$\psi_s = \frac{VR_s}{VR_s + VR_d} = \frac{K_s E_s}{K_s E_s + K_d E_d} \tag{9}$$

The expression EC fraction can be written as:

$$\psi_d = \frac{K_d E_d}{K_s E_s + K_d E_d} \tag{10}$$

To determine the machinability constant of the simultaneous ED/PEC drilling, Eqs. (3) and (11) are used and was obtained K_{hyb}, which is defined as Eq. (12):

$$MRR^p * t_c = K_s * E_s + K_d * E_d = K_h * (E_s + E_d) \tag{11}$$

$$K_{hyb} = \frac{K_s E_s + K_d E_d}{E_s + E_d} \tag{12}$$

A simplification of Eq. (3) in terms of machinability constants for the hybrid K_{hyb}, the contribution fraction ψ_s of the ED process in Eq. (9) and the final contribution fraction ψ_d of the EC process in Eq. (10) results in Eq. (13), and it is solved by obtaining the experimental constants for the LR-DW condition of the simultaneous ED /PEC drilling. A resistivity range, in the order of 0.5 to 2.5 MΩcm is used to obtain the hybrid machinability constant K_h, where the pulsed activation time of each constituent ED and EC are fractions of the active time condition of the ED /PEC simultaneous process.

$$MRR_{hyb} = K_h * A_T \left[\left[\frac{1}{t_c} * \int_0^{ton,ED} (Ie * V\ )dt \right] + \left[\frac{1}{t_c} \int_0^{ton,EC} \left[V_a * i_o * exp\left(\eta_{Fe} * \beta^{-1}{}_{a,Fe}\ \right) \right] dt \right] \right] \tag{13}$$

A methodology was developed that allowed to reproduce the basic processes ECM, EDM and the hybrid ED/PEC considering the drilling process in the test materials, HSLA high-strength steel, in thicknesses of 9.5 mm, to compare the speed of material removal (MRR). Preparation of 32 samples of 9 x 12 x 35 mm of HSS-550 (HSLA). A state of the art search was carried out in the hybrid electro-ionic-based ECM and electroplasma-based EDM processes, which supports the knowledge base for the development of the simultaneous hybrid ECM + EDM model.

2.5 Experimental parameters for experimental drilling EDM, ECM and S-ED/PEC

To validate the proposed model with the observation, measurement and comparison of the electro-thermal/electro-ionic effect on the workpiece in High Strength Steel Low Alloy (HSLA), the microstructure at the cutting front was evaluated for each condition EDM, ECM, and compared against the simultaneous hybrid S-ED / PEC. The drilling parameters of each system were established according to the theoretical framework developed, for the different EDM, ECM and S-ED / PEC processes in different media as shown in **Table 1**. Similarly, the parameters for the ECM, EDM and S-ED/PEC processes were defined as shown in **Table 2**, which were used in the proposed experiment designs for each route according to the methodology. The parameters were determined based on the

Machining process	Medium/electrode	Type	Magnitude	Voltage DC
ECM	Electrolyte	Acid Solution [Na2NO3 + H2SO]	∼10 Ω.cm	Continuous
EDM-OILD	OILD Dielectric	Oil	∼ 10 MΩ.cm	Pulsed
EDM-DW	DW Dielectric	[H2O] ∼Deionizade	2.5 MΩ.cm	Pulsed
S-ED/PEC	Semidielectric (LR-DW)	[H2O] + [NaBr]	0.5 a 2.5 MΩ.cm	Pulsed
ECM	Electrode	Tube SS-304	∅ 2.5 mm δ 250 μm	Pulsed
S-ED/PEC	Electrode	Tube Cu-Sn	∅ 500 a 1000 μm δ 100 a 150 μm	Pulsed

Table 1.
Specification for ECM, EDM and S-ED/PEC machining [16].

Parameters	Simbology	Values	Units	Condition
Voltage	VS1,VS3	12,30,45	Volts	Variable
Gap Voltage	VG	45,60	Volts	Variable
Current	I_c	10, 15, 25	Ampers	Variable
Pulsed time	t_{on}	12,20,28	μS	Variable
Cycle Duty	DC	0.3,0.5,0.7	%	Variable
Frecuence	τ^{-1}	25000	Hz	Constante
Resolution	V_z	1,5	μm	Constante
Cutting Deep	H	3.0, 3.5	mm	Constante

Table 2.
Parameters for ECM, EDM and S-ED/PEC machining [16].

electrical range Vs, discharge start voltage from 30 to 45 Vdc, and electrochemical resistivity, 0.1 to 0.5 MΩ · cm, which allows a stable and reproducible ED + EC hybridization [18].

3. Discussion and results

The profile of the electrical signals for EDM and ED / PEC simultaneous drilling is presented in **Figure 6**. In particular, a typical electrical signal for the EDM process is shown in aqueous medium in deionized water at 2.5 MΩ · cm. **Figure 6(a)** shows the results of the energy transferred $E_s(t)$ during the ED cycle considering the area under the curve of the relationship Voltage Vs Current. **Figure 6(b)** reveals the results of the pulsed electrical signal, which was modified using a resistivity close to 0.5 MΩ · cm in deionized water adjusting the solution with NaBr ions. The result is a simultaneous ED/PEC behavior where the current wave was monitored with a decrease in the Faraday current. Where a division of the electrical signal is seen in two energy regions: in the first section of the current profile, up to where the current plateau ends, the energy magnitude $E_s(t)$ is obtained, which is determined by the process ED; while the current decays exponentially to a value close to the nominal current I_o, it is possible to obtain a second region of energy $E_d(t)$, which results from the EC process, for each pulse or duty cycle with a duration of 28 μs.

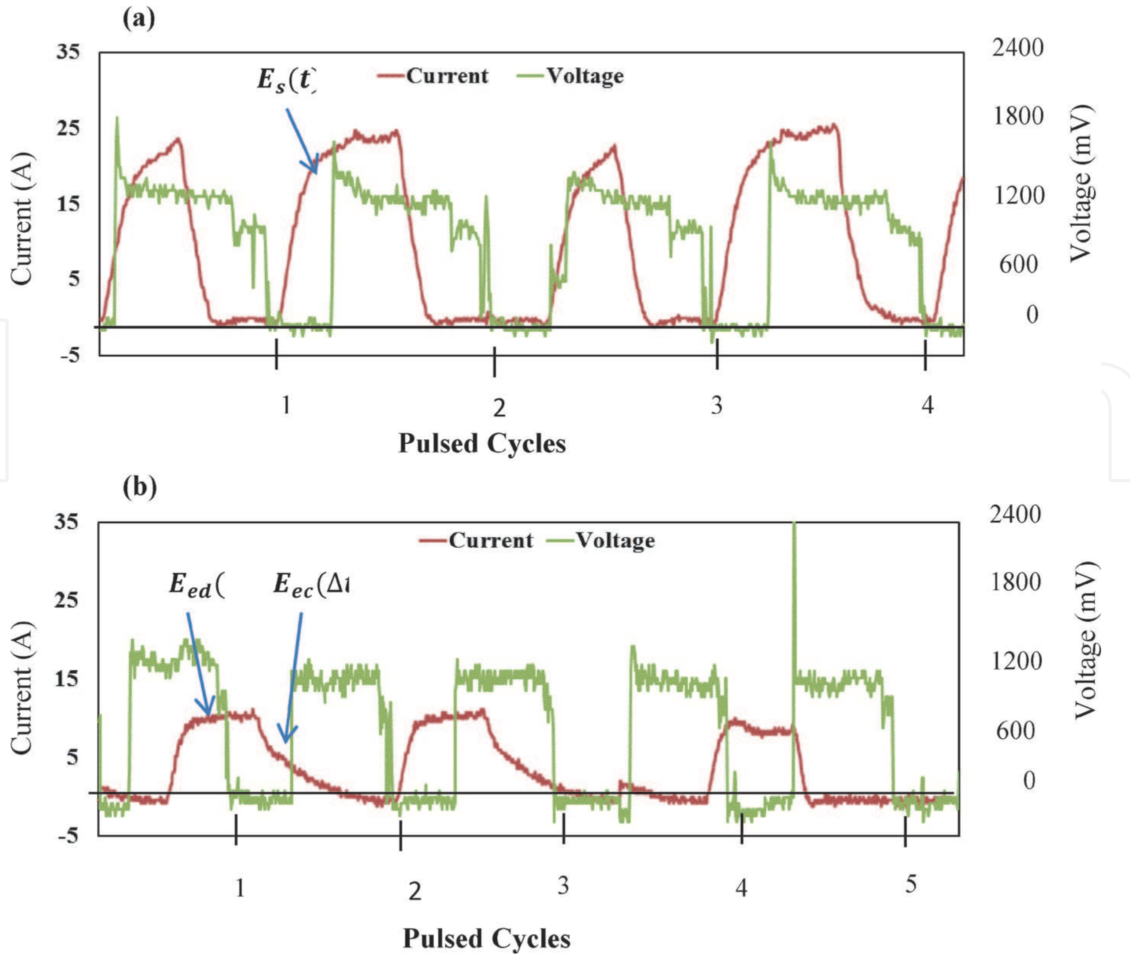

Figure 6.
Showed electrical signal performance using a 25 kHz pulsed with DC 70% during (a) EDM and (b) hybrid ED/PEC [16].

The values of energy transferred and machinability constant shown in **Table 3**, for the theoretical model MRR_{hyb} represented by Eq. (13), are determined under two power conditions, 25A and 15A. Eqs. (5), (7) and (12) obtain the values of the transferred energy E_s, E_d y E_{hyb}, while the machinability constants K_s, K_d, K_h were obtained from Eqs. (3) and (12). Eqs. (9) and (10) estimate the energy fraction ψ_s for ED and the energy fraction ψ_d for EC, which contributes to S-ED/PEC machining.

The response of the theoretical model is shown in the MRR profiles for the ED/PEC and EDM processes. **Figure 7** shows the profiles of the increase in MRR for

Magnitudes	High power (25 A/45 V)	Low power (15A/30 V)
$E_s\ [J \cdot cycle^{-1}]$	1125	450
$E_d\ [J \cdot cycle^{-1}]$	45	27
$E_{hyb}\ [J \cdot cycle^{-1}]$	1170	477
$K_s\ [mm^3 \cdot mm^{-2} \cdot J^{-1}]$	4.342 x 10^{-4}	5.497 x 10^{-4}
$K_d\ [mm^3 \cdot mm^{-2} \cdot J^{-1}]$	1.734 x 10^{-5}	2.180 x 10^{-5}
$K_h\ [mm^3 \cdot mm^{-2} \cdot J^{-1}]$	5.070 x 10^{-4}	6.651 x 10^{-4}
ψ_s	0.924	0.907
ψ_d	0.075	0.092

Table 3.
Transferred energy for S-ED/PEC machinability [16].

EDM, in a response surface methodology (RSM) using Design-Expert® Software Version 10.0. As the pulse duration increases, the MRR increases as shown **Table 4**, a trend similar to that reported by Shabgard and Akhbari [19]. They report the effect of discharge current and pulse duration for EDM and ECDM, respectively. In this analysis, it was observed that when the current decays, it is necessary to increase the pulse duration, to maintain a constant MRR profile.

The resistivity analysis for MRR during ED /PEC is shown in **Figure 8**, with a LR-DW NaBr medium, in the range of 0.5 to 2.5 MΩm at 15A. **Figure 8(a)**, the response surface analysis shows the duration of the pulse versus the resistivity of the electrolyte. The MRR exhibits a slight increase in low resistivity near the 0.5 MΩ.cm condition at 12 μs. When the resistivity exceeds 1.5 MΩ.cm, the system works in the EDM condition, there is a transition point from the EC to ED condition. This is observed in **Figure 8(b)**, the response in the removal of MRR material as a function of the Voltage for different levels of resistivity of the medium, a low voltage region of the MRR profile is appreciated at 8 mm^3/min, where it reveals an inflection point, where the resistivity is greater than 2.0 MΩcm. This finding is consistent about the ED/EC transition that exists in the low resistivity medium for EC was reported by NGuyen et al. [20]. Under conditions similar to ECM where the system operates under low current and voltage conditions.

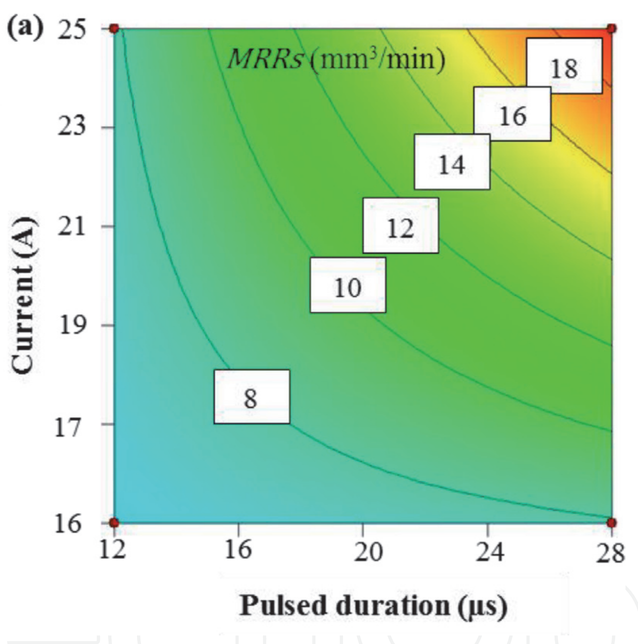

Figure 7.
Response surface analysis for material removal rate MRR during EDM at 2.5 MΩcm/45 V [16].

Parameters	EDM	ECM	S-ED/PEC
MRRv (mm^3/min)	20 a 22	2.8 a 3.4	23–28
Over cutting (%)	<30	40 a 120	<36
White layer (μm)	3.0 a 6.5	0	0.5 a1.5
HAZ (μm)	10 a 20	0	<6.25
Hardening HV	320 a 380	MB	<300
Quality	Poor(microfails)	Excellent	Good

Table 4.
Comparison of EDM cutting processes ECM and S-ED/PEC for HSS Domex 550C [16].

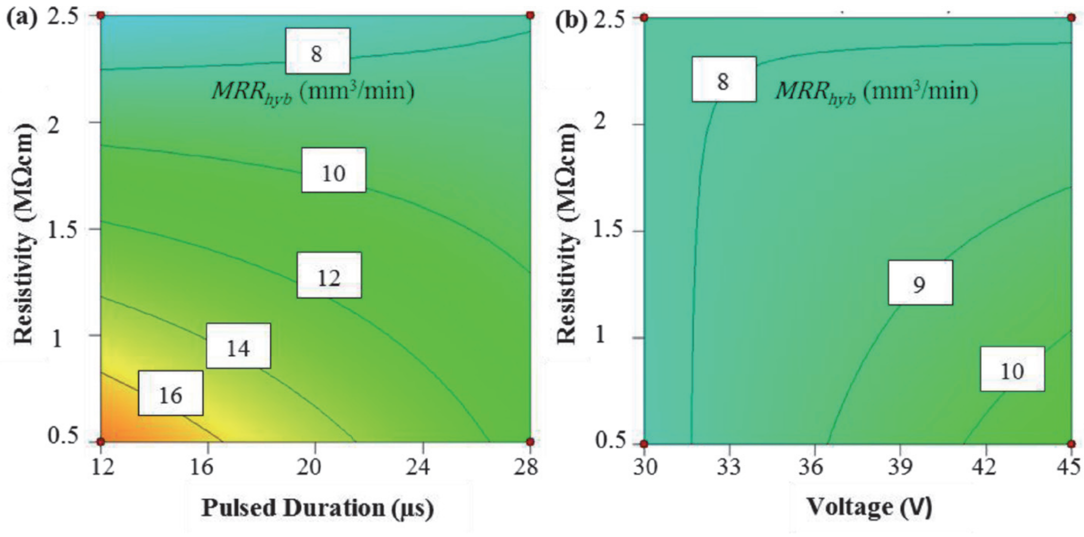

Figure 8.
Response analysis of MRR_{hyb} for (a) ED/PEC at 15A, 45 V and (b) ED/PEC at 15A and pulse duration of 12 μs [16].

Figure 8(b) presents the results of the simultaneous ED/PEC sensitivity analysis to estimate MRR applying the theoretical model using a NaBr LR-DW in a 0.5 MΩcm medium. The two regions are clearly separated in a current close to 19A and with a pulsatile duration of 20 μs at the pulsed voltage. The first region is defined as a low current of less than 20 μs and, since it is primarily electrochemical, it is in the region of the ECM. The second region is in the high current range, that is, above 20 μs, and because it is primarily an electrical discharge process, it is in the ED Region. Therefore, ED → ECD → PEC processes produce simultaneous ED/PEC, and when higher currents occur with low pulse durations, the passivation effect occurs in the ECM condition. In the same way, high pulse durations with lower currents result in a low MRR.

Figure 9, compares the experimental results with the theoretical model of MRR_{hyb} for the EDM material removal rate and simultaneous ED/EC drilling. The MRR_{hyb} is formed by two conditions, material removal of ED and EC simultaneously. When the pulse duration is increased, the effect in both cases is an increase in the rate of material removal, also determined that the effective sparks are determined by the duration of the pulsed signal and the analysis of the removal of

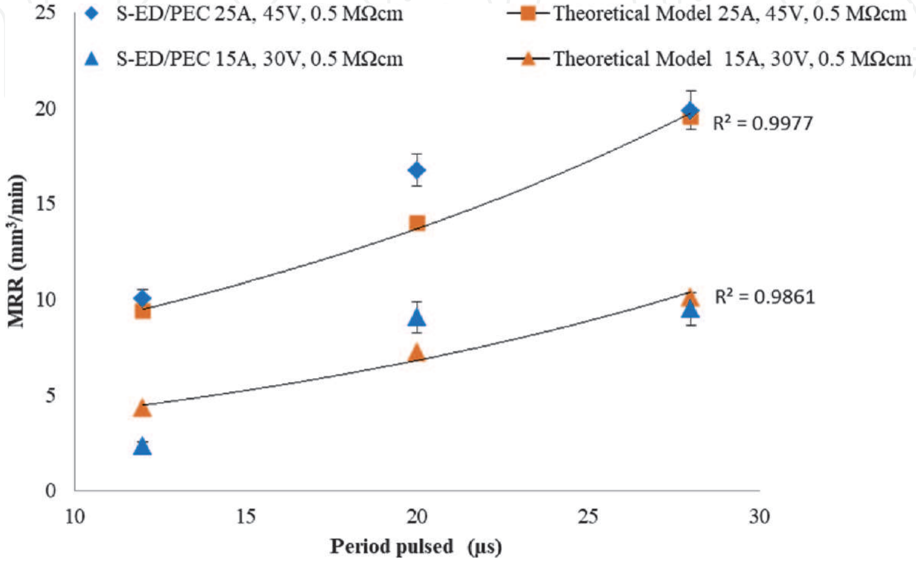

Figure 9.
Comparison of the experimental MRR versus theoretical model for ED/PEC drilling in HSLA steel [16].

material by discharge is significantly increased. However, the current has a greater effect on the MRR, because it generates an increase in the energy transferred to the workpiece, and associated with long periods of time produces a higher material removal rate and effect of surface roughness [21]. An MRR behavior at high current increases to 5 mm^3/min by 10 μs. While the increase for a low discharge current is 2.5 mm^3/min for 10 μs. This is consistent with the ECM process, which exhibits effective material removal rates in the range of 1.51 $mm^3/(A \cdot min)$ to 2.13 $mm^3/(A \cdot min)$ and that the speed increases as the density of current [22].

4. Conclusions

The analytical correlation of the mathematical model and the experimental results of the cutting face for simultaneous S-ED/PEC drilling using medium to low resistivity for drilling in HSLA material were established as follows.

1. A proposed parametric model for the simultaneous S-ED/PEC was developed against the experimental data to determine the MRR with an acceptable correlation close to 0.99, which was possible to obtain a machinability constant in the range of 5.07×10^{-4} a 6.65×10^{-4} $(mm^3 \cdot mm^{-2} \cdot J^{-1})$. The proportion of energy transferred that contributes to individual processes for simultaneous ED/PEC was estimated at ψ_s = 0.9246 for the ED fraction and ψ_d= 0.0753 for the EC fraction.

2. The effect of resistivity in the response sensitivity analysis, with respect to the material removal rate for simultaneous S-ED/PEC drilling, results in a change in direction of the MRR, specifically when the resistivity is less than 1.5 MΩ · cm. For the PECM contribution, at higher voltages with lower current, a slight increase in MRR occurs.

3. The effect of overheating in the EDM process increases the HAZ layer, so that it is six times greater than that obtained by the S-ED/PEC drilling of LR-DW. The results indicate that the contribution of PECM allowed the material removal mechanism to reduce the involvement in the microstructure through assisted dissolution.

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Abbreviations

A	Symmetry factor
A	Abrasive
AECH	Abrasive Electro Chemical
AED	Abrasive Electrical Discharge
AEDM	Abrasive Electrical discharge machining
$\beta_{a,Fe}$	TAFEL anodic constant $\left[mV^{-1}\right]$

δ	Tooling thickness (μm)
η_{Fe}	Anodic over potential of iron $[mV]$
$\phi_{a,Fe}$	Anodic potential of iron $[mV]$
ϕ^0	Standard potential $[mV]$
$i_{o,Fe}$	Current of ion-exchange of iron $[A]$
φ	Volume fraction by cycle
ψ_s	Energy share factor ED
ψ_d	Energy share factor EC
$\Delta t_{on,ED}$	Active differential time for ED $[s]$
$\Delta t_{on,EC}$	Active differential time for EC $[s]$
A_T	Drilling area [mm2]
CHM	Chemical Machining
CHP	Chemical Pressure Jet
DW	Deionized water dielectric
LR-DW	Low-resistivity deionized water
EBM	Electro Beam Machining
EC	Electrochemical process
ECM	Electro chemical Machining
ED	Electro discharge process
EDM	Electro Discharge Machining
ELB	Electron Laser Beam
E(t)	Energy transferred $\left[J \cdot cycle^{-1}\right]$
E_d	Energy transferred for EC $\left[J \cdot cycle^{-1}\right]$
E_s	Energy transferred for ED $\left[J \cdot cycle^{-1}\right]$
E_h	Energy transferred for SEDCM hybrid $\left[J \cdot cycle^{-1}\right]$
f_e	Factor of equivalent current
F	Faraday constant $\left[C \cdot mol^{-1}\right]$
F	Fluid
F_{in}	LR-DW/DW internal flow $\left[mm^3 \cdot min^{-1}\right]$
F_{out}	LR-DW outside flow $\left[mm^3 \cdot min^{-1}\right]$
FM	Forces Magnetohydrodynamic
G	Grinding
GUS	Grinding Ultrasonic
I_e	Current wave equivalent $[A]$
I_F	Faraday current $[A]$
I_p	Current of wave peak $[A]$
K_m	Machinability constant $\left[mm^3 \cdot m^{-2} \cdot J^{-1}\right]$
K_d	Machinability constant for EC $\left[mm^3 \cdot m^{-2} \cdot J^{-1}\right]$
K_s	Machinability constant for ED $\left[mm^3 \cdot m^{-2} \cdot J^{-1}\right]$
K_h	Machinability constant SED/PEC$\left[mm^3 \cdot m^{-2} \cdot J^{-1}\right]$
LBM	Laser Beam Machining
MCP	Mechanical cutting plasm
MRR^p	Planar material removal rate $\left[mm^3 \cdot m^{-2} \cdot s^{-1}\right]$
MRR_d^p	Planar material removal rate EC $\left[mm^3 \cdot m^{-2} \cdot s^{-1}\right]$
MRR_s^p	Planar removal rate for ED $\left[mm^3 \cdot m^{-2} \cdot s^{-1}\right]$
MRR_s	Material removal rate for ED $\left[mm^3 \cdot min^{-1}\right]$
MRR_{hyb}	Material removal rate for SEDCM $\left[mm^3 \cdot min^{-1}\right]$
LAE	Laser Abrasive Electrolyte
LAT	Laser Abrasive Turning
LEM	Laser Electrochemical Machining

PBM	Plasm Beam Machining
R	Ideal gases constant $[J \cdot mol^{-1} \cdot K^{-1}]$
RSM	Response Surface Methodology
R_m	Average radius [μm]
S-ED/PEC	simultaneous ED/CM drilling
S_o	Tooling-workpiece gap $[mm]$
t	Time $[s]$
t_c	Cycle time $[s]$
t_i	Iterative time $[s]$
t_{on}	On-time $[s]$
t_{off}	Off-time $[s]$
T	Temperature $[K]$
T	Turning
Th	Thermal
UAEDM	Ultrasonic Abrasive Electrical Discharge Machining
UALBM	Ultrasonic Abrasive Laser Beam Machining
UAT	Ultrasonic-Abrasive Turning
USECM	USECM Ultrasonic Electrochemical Machining
USMEC	Ultrasonic Mechanical - Electrochemical
US	Ultrasonic
USG	Ultrasonic- Grinding
USP	Ultrasonic Pressure Jet
V_a	Anodic voltage $[mV]$
V_s	Pulsed voltage of source $[V]$
VR	Removal volume rate $[mm^3]$
VR_d	Removal volume rate for ED dissolution $[mm^3]$
VR_s	Removal volume rate for ED spark $[mm^3]$
z_0	Initial reference z-axis
Z	Numbers of electrons exchange-redox

Author details

Jesus M. Orona-Hinojos[1,2]

1 Quimmco Innovation System, San Pedro Garza García, N.L., Mexico

2 Corporación Mexicana de Investigación en Materiales Quimmco Innovation System. San Pedro Garza García, N.L., México, USA

*Address all correspondence to: jesus.orona@quimmco.com

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